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Design and Demonstration of a New Small-Scale Jet Noise Experiment

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A facility capable of acoustic and velocity field measurements of high-speed jets has recently been built and tested. The anechoic chamber that houses the jet has a 2.1 m $\times$ 2.3 m $\times$ 2.5 m wedge tip to wedge tip working volume. We aim to demonstrate that useful experiments can be performed in such a relatively small facility for a substantially lower cost than in larger facility. Rapid prototyping allows for quick manufacturing of both simple and complex geometry nozzles. Sideline and 30° downstream acoustic measurements between 400 Hz and 100 kHz agree well with accepted results. Likewise, nozzle exit-plane data obtained using particle image velocimetry are in good agreement with other studies.

I. Introduction

Aviation jet noise is heavily regulated with additional restrictions anticipated in the future. In the United States, for example, the FAA's FAR 36 Stage 4 noise standards came into effect in January 2006 for vehicles with a maximum take off weight of over 12,500 lbs, demanding a 10dB EPNL (effective perceived noise level) reduction beyond the previous Stage 3 limits.[1] International standards are typically at least as restrictive and must be satisfied by any commercially viable business jet. Many current aircraft operate close to FAA and other limits. Predicting the impact of jet configuration and placement modifications on noise generation is a significant challenge, because jet noise levels can be sensitive to nozzle configurations and because there is no experimental or numerical substitute for a full-scale experimental engine test. However, relatively inexpensive, small-scale tests can help avoid full-scale tests to assess the noise impact of design modifications and study noise mechanisms.

For the experiments reported here we used a new small anechoic chamber constructed at the University of Illinois at Urbana-Champaign. This is the first report on this facility and its validation. Its design was guided by the recommendations of Ahuja,[2] as well as consideration of previous facilities whose design and use have been reported.[3–5]

II. Experimental Facility

The facility is a 2.1 m $\times$ 2.3 m $\times$ 2.5 m wedge-tip-to-wedge-tip testing anechoic chamber for aeroacoustic and velocity field testing of around 2.54 cm nominal inner-diameter nozzles. The cloth covered fiberglass wedges were manufactured by Eckel Industries to have a low cutoff frequency of 250 Hz, tested in accordance with the Impedance Tube Method-ASTM-C 384-90. Above this frequency they are reported to absorb 99% of the incident energy. We confirm their near-anechoic behavior in Section V. Due to the location of the microphones the actual cutoff is closer to 400 Hz, which is still below the range of interest in the facility. This was determined per the ISO 3745 standard that microphone locations must be 1/4 wavelength (at cut-off)

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¶Professor, Departments of Mechanical Science & Engineering and Aerospace Engineering, University of Illinois, Senior Member AIAA from the wedge tips.[6] The walls of the chamber were constructed using standard wood-stud framing with a maximum center to center distance of 40 cm. An image of the completed facility is shown in Figure 1. To reduce outside noise, five 5.08 cm × 5.08 cm × 2.54 cm thick polyurethane rubber feet were installed between each of the nine supports and the concrete slab floor of the lab.

Air is supplied to the experimental facility from a series of pressurized tanks (total 140 m^3 of air at 890 kPa). These tanks are charged by a 224 kW Ingersoll-Rand SSK HPE300 compressor, which both dries and filters the air. Due to the relatively large amount of air contained in the tanks and the small amount of mass flow required by the jet, 2.54 cm and smaller nozzles can be tested continuously. To minimize spurious acoustic contamination sources, large 20.3 cm piping is used from the compressed air tanks to the control valve that regulates the jet flow.

The control valve is a 2.54 cm Fisher 667-ET-DVC6010 Globe Valve Assembly with carbon steel body used in conjunction with manual control from a Honeywell DC1203-7-7-8-1-1-0-0-0 Model UDC1200 Process Controller to keep the flow constant despite any slow pressure variations in the supply tank pressure. It has been found that manual control using pressure readings further upstream, near the nozzle exit, is able to better set the jet velocity than automated control using the components delivered with the valve. The manufacturer specified noise from the valve is less than 83 dB.

Special attention was given to replacement air, to make up for that entrained by the jet and exhausted

Figure 1: The anechoic jet noise facility.

with it out of the lab. We estimate the amount of air needed based upon a reported relationship for turbulent jet entrainment from the experimental measurements of Ricou and Spalding:[7]

$$\frac{m}{m_o} = 0.32\frac{x}{D} \tag{1}$$

where m is the mass flow rate of entrained air, m_o is the mass flow of the jet, x is the distance along the jet axis measured from the nozzle exit, and D is the nozzle diameter. Using this relationship for our 2.54 cm jet at Mach 0.98, it was determined that there will be roughly 4.8 kg/s of air entrained by the jet before it enters the exhaust ducting. To provide this make up air, two open sections have been installed in the upstream wall of the chamber partially inspired by those in the anechoic facility at The Ohio State University.[5] These sections are rectangular in cross section, 2.1 m in height and 0.28 m in width. The estimated velocity of air entering through these entrainment sections is 3.5 m/s, which is about one-hundredth the velocity of the jet. This make-up air is filtered by an aluminum woven-wire screen with 0.1 cm mesh size. The two make-up air sections have a 2.54 cm thick acoustic polyurethane foam absorber lining with egg carton shape to reduce any spurious noise from the lab from entering through these sections. They are also designed with an overhang such that there is no direct line of sight from the lab into the chamber.

The exhaust consists of a conical 1.2 m diameter bell mouth leading to a 0.6 m × 0.6 m exhaust duct. The exhaust system is made of acoustically absorbing perforated metal ducting, and the flow is directed outside the building smoothly using aerodynamic turning vanes, as shown in Figure 2, to reduce the potential for downstream disturbances to contaminate the measurements in the chamber.

The microphones used for all experimental acoustic measurements performed are Brüel & Kjær type

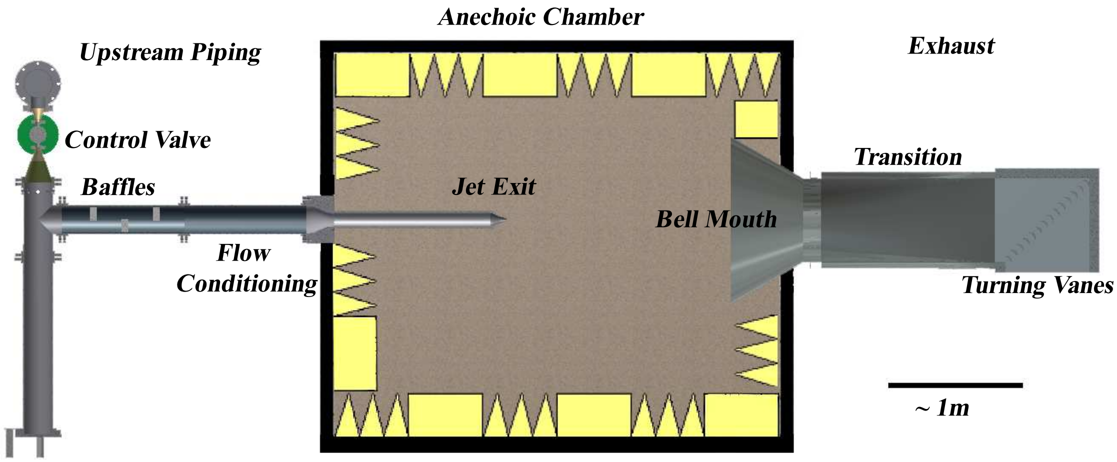


Figure 2: Anechoic facility overview schematic.

4939 0.635 cm free-field microphones. These microphones are designed for high-level and high-frequency measurements with a flat response up to 100 kHz.

III. Facility Characterization

Since its completion in early 2010, the anechoic facility has undergone successive modifications to improve the quality of the data acquired. Example preliminary 1/3-octave measurements taken in the facility are shown in Figure 3. (All acoustic measurements for this paper are for uniform stagnation temperature cold jets.) The multiple spectral peaks are obviously spurious, a clear sign of problems with the original facility design. From this start the facility was improved in a step by step process, finally resulting in the current facility, which is able to reproduce accepted jet noise data. Some of the modifications made are discussed to illustrate the evolution of the facility to its current capability to match accepted data. After every modification the facility was retested and compared to accepted measurements to assess improvements. A few of the more significant improvements are shown here.

Among the first modifications made was the addition of a flexible polyurethane foam lining to the upstream piping in the two horizontal sections before the first contraction (see Figure 2). This was done to reduce any noise created in this section as well as attenuate noise from upstream. Care was taken to avoid introduction of a step or other such points of potential flow separation. This involved the manufacture of transition pieces of foam that ran smoothly from a 17.8 cm inner diameter of the foam lined section back out to a 20.3 cm inner diameter to match the beginning of the contraction, shown in Figure 4.

The lining improved results, but the noise levels were still unacceptably high, so three baffles made from Sonex One acoustical foam were inserted into one of the sections of the 20.3 cm piping, shown in Figure 5. The baffles were fashioned entirely out of foam and inserted to block any direct line of sight from upstream to the jet exit as shown in Figure 5. Previous researchers have used perforated metal shells with fiberglass baffles,[2] however we wished to avoid any reflections from the metal casing. The baffles were spaced to be incompatible with the obvious standing wave modes of the pipes.

A 2.54 cm thick piece of honeycomb (3.18 mm cell size) was placed downstream of the baffles in the 20.3 cm piping section followed by an aluminum screen (1.02 mm cell size). Both components were placed upstream of the 20.3 cm to 10.2 cm contraction and were designed to suppress turbulence. They were positioned after the baffles to reduce any non-uniformity imposed on the flow by the baffles. After this final screen, the flow path is smooth and therefore is not expected to create significant noise. The screen was placed downstream of the honeycomb following the recommendation of Pope.[8]

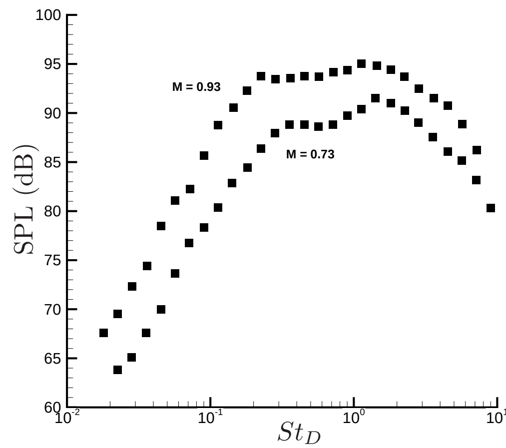
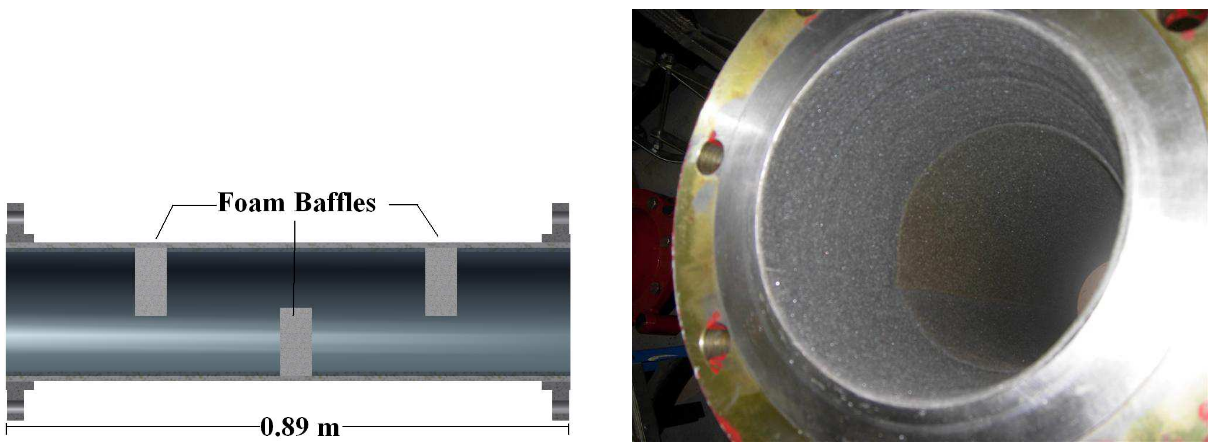


Figure 3: Sideline $\theta = 90°$ 1/3-octave band spectra showing spurious peaks from preliminary tests.



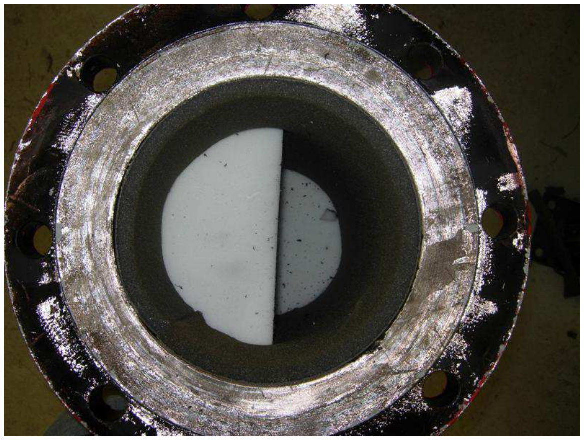
(a)

(b)

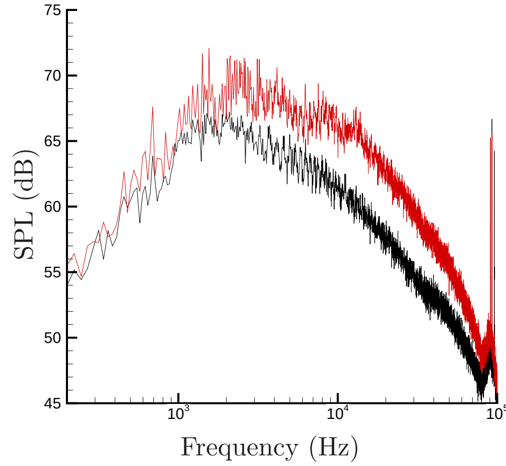
Figure 4: Upstream acoustic conditioning: (a) staggered baffles in the upstream muffler section and (b) foam lining and tapered transition piece in the upstream piping.

At this point in the facility development, there was still evidence of reflections within the chamber. The seemingly largest source was investigated first: the exhaust collector, which was thought to act as a giant reflector plate downstream of the jet. The effect was so pronounced it was discernible with the human ear while standing inside the chamber. To correct this, the entire collector was coated in the same polyurethane foam material used to line the upstream piping. This removed the low-frequency obviously spurious hump from the spectrum as shown in Figure 6. This effect at low frequencies was expected given reported experience with poor anechoic chamber designs leading to contamination of jet noise spectra at similarly low frequencies.[9]

Once the facility appeared to be free of spurious noise, various tests were performed to confirm that accurate jet noise data was indeed being acquired. One of these methods was comparing the overall sound level at different flow conditions with jet velocity (U_j) to the eighth power. This scaling is followed closely between Mach numbers of 0.4 and 0.98. Mach number throughout this paper is defined with relation to the speed of sound in the core of the jet. Deviation from the U_j^8 at low Mach number marks the minimum speed at which the facility can operate before rig noise becomes dominant. In our case, this occurs near Mach 0.4.



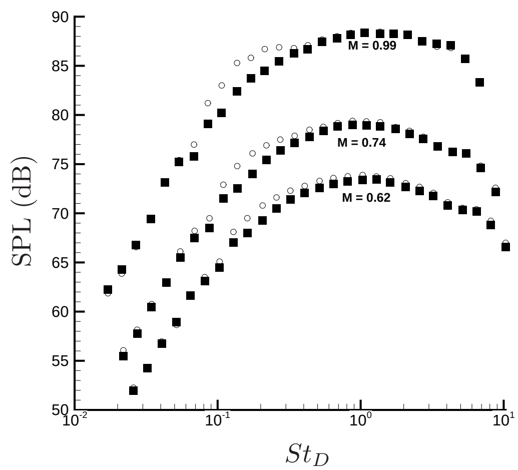
(a)



(b)

Figure 5: (a) Foam baffles in the upstream piping and (b) the resulting improvements in noise measurements at Mach 0.74: Red - Without Baffles; Black - With Baffles. (The high-frequency tone in (b) was due to microphone grid-cap interference and corrected in subsequent facility improvements.)

(a)



(b)

Figure 6: Exhaust collector improvement: (a) foam on the downstream collector with (b) resulting improvements in noise measurements: ○ - Before; ■ - After.

IV. Atmospheric Absorption

Atmospheric absorption can play a significant role, especially at higher frequencies, and is particularly a concern in small scale facilities, since so much of the spectrum is high frequency. As the jet spectra scales inversely as nozzle size, smaller nozzles require measurements at higher frequencies. A correction must be applied so that all data can be compared in their lossless form. Viswanathan[10] discusses several methods for calculating atmospheric absorption coefficients and for small-scale facilities recommends the method of Shields and Bass,[11] which he deemed superior for high-frequency measurement to the SAE method,[12] which is used for full-scale engine corrections. At lower frequencies (such as those of importance in full-scale tests), these two methods produce similar results, however at higher frequencies the deviation can be significant. After consulting the ANSI standard[13] as well as information from Viswanathan,[10] it was determined that the

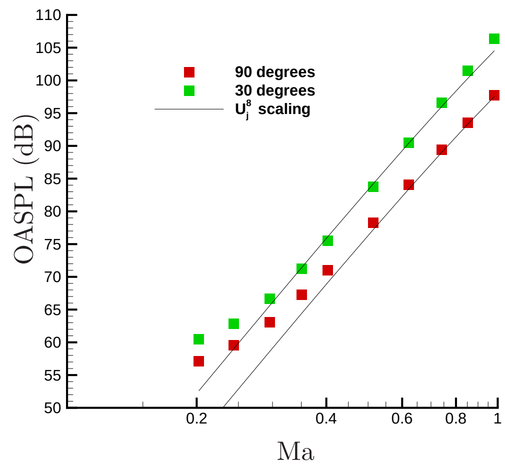


Figure 7: Comparison of OASPL with U_j^8 scaling at both 30° and 90°.

equations given by the ANSI standard produce results that are effectivly indistinguishable from the Shields and Bass approach.[11] We thus employ the ANSI standard. The attenuation coefficient, in decibels/meter, is:

$$\alpha(f) = 8.686 f^2 \left[1.84 \times 10^{-11} \left(\frac{p_a}{p_r}\right)^{-1} \left(\frac{T}{T_r}\right)^{\frac{1}{2}} + \left(\frac{T}{T_r}\right)^{-\frac{5}{2}} \left\{ 0.01275 \exp\left(\frac{-2239.1}{T}\right) \frac{f_{rO}}{f_{rO}^2 + f^2} + 0.1068 \exp\left(\frac{-3352.0}{T}\right) \frac{f_{rN}}{f_{rN}^2 + f^2} \right\} \right] \tag{2}$$

α - Attenuation Coefficient (dB/m)
f - Frequency (Hz)
p_a - Atmospheric Pressure
p_r - Reference Pressure (101325 Pa)
T - Atmospheric Temperature (K)
T_r - Reference Temperature (293.15 K)
f_{rO} - Relaxation Frequency for Oxygen (see appendix)
f_{rN} - Relaxation Frequency for Nitrogen (see appendix)

V. Anechoic Chamber Characterization

The purpose of an anechoic chamber is, of course, to simulate a free-field environment in a laboratory. To establish that the chamber was indeed acceptably anechoic, it was tested with known sources and without any airflow. To a good approximation, sound did decay as $1/R^2$, where R is the distance from the noise source. These tests were performed using a white noise source positioned at the typical jet exit location. Frequencies up to the 20kHz limit of the noise source were tested. Example results are shown in Figure 8. It is clear that the facility is anechoic down the the expected 400 Hz cut-off frequency.

VI. Complex Nozzle Capabilities

An on-campus rapid prototyping shop allows for fast manufacture of new nozzle designs. These nozzles are made on a Formiga P 100 Selective Laser Sintering system (SLS) at a cost of \$0.30 per gram of material. With such technology, complex shapes that would be difficult (and expensive) to manufacture using traditional metal designs can be made quickly and at roughly the same cost as their baseline counterparts without the

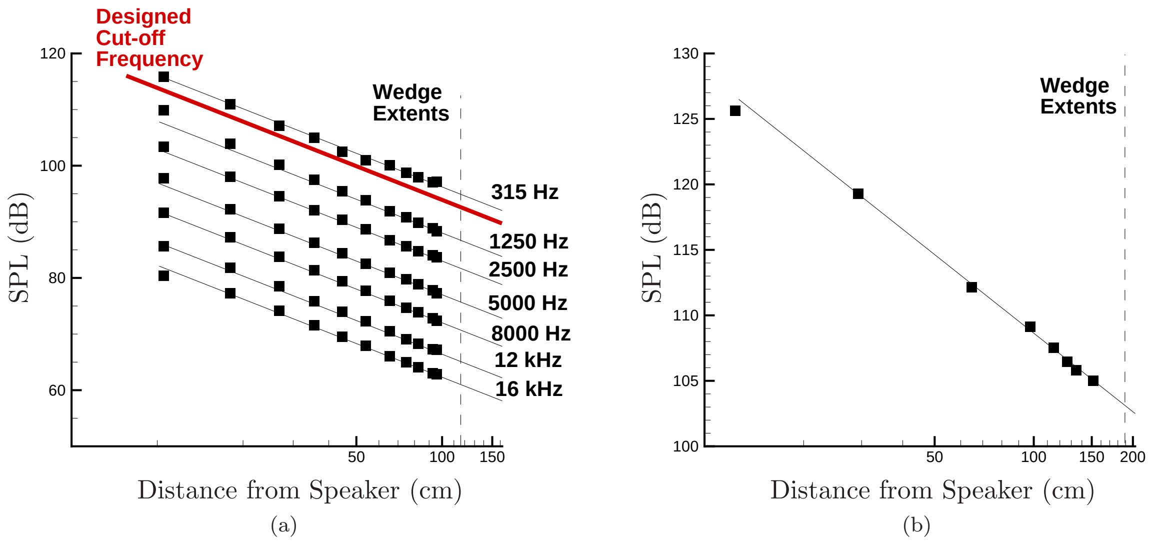


Figure 8: Experimental measurements of sound field spherical divergence in chamber ■ and — $1/R^2$: (a) sideline 90° at individual frequencies; (b) downstream 30° OASPL.

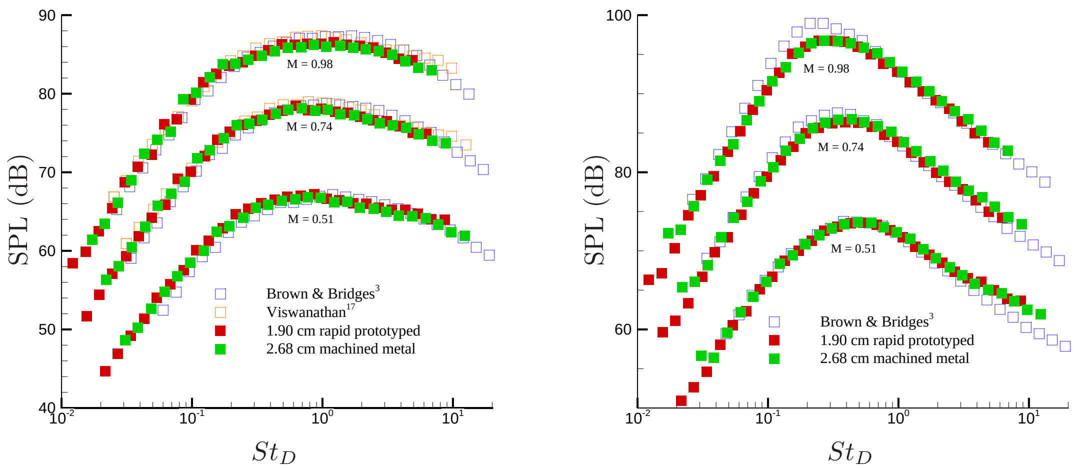
complex geometries, all with sub-millimeter resolution.[16] Sample simple designs which have been made and tested are shown in Figure 9. The chevron nozzle has been designed so the position of the chevrons can be rotated in relation to the microphone array which is fixed. When scaled appropriately, these nozzles were found to behave consistent with the metal nozzle which was used to characterize this facility. After testing various sized nozzles, it was determined that the 1.90 cm diameter nozzle was the smallest exit area which could produce scalable data, attributed to Reynolds number effects by Viswanathan.[17]

In order to validate the facility, measurements were compared with accepted experimental data[3,17] in

Figure 9: Nozzles designed and manufactured with rapid prototyping: (a) Standard Contraction; (b) Chevron Nozzle.

Figure 10. The data are in excellent agreement, except for Mach 0.98 measurements taken at 30°. The disagreement near the peak of the spectrum has not been determined as of this time. Also shown is a comparison between a 2.68 cm copper nozzle and a 1.90 cm nozzle made at a cost of about $10 utilizing the rapid prototyping technology available. The data again are in excellent agreement except for the most intense 30° data for the M = 0.98 jet. The cause of the difference is uncertain, and it currently remains unclear why the present facility is modestly quieter near the peak spectral frequencies. Also, nozzles manufactured using different techniques are able to produce consistent noise spectra when scaled. These data are presented in

lossless form with atmospheric absorption effects removed per the method described above in Section IV. The data are also corrected to distances based on nozzle diameter assuming spherical divergence.



(a) (b)

Figure 10: Typical 1/3 octave far-field response corrected to lossless conditions at 72D: (a) sideline 90°; (b) downstream 30°. Filled points are from the present facility.

VII. Particle Image Velocimetry

Particle image velocimetry measurements were made at the exhaust of the jet with a Gemini New Wave dual head Nd:YAG laser used for illumination. The images were acquired with a PCO.1600 CCD camera capable of 1600 × 1200 pixel images. At least 1000 image pairs were taken. The jet flow was seeded with Bis(2-ethylhexyl) sebacate (DEHS) and a Vicount 1300/180/2.2 kW smoke generator was used to seed the entrained air. All image processing was done using DaVis from LaVision. Shown in Figure 11 is a mean velocity field. In Figure 12 is a comparison of $u'v'$ with Ukeiley.[18] Good agreement is observed with the present data.

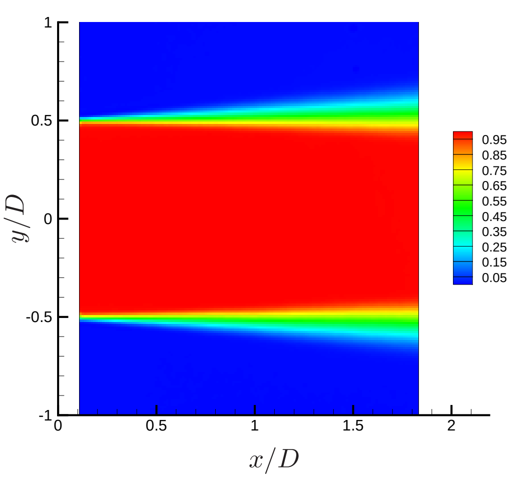
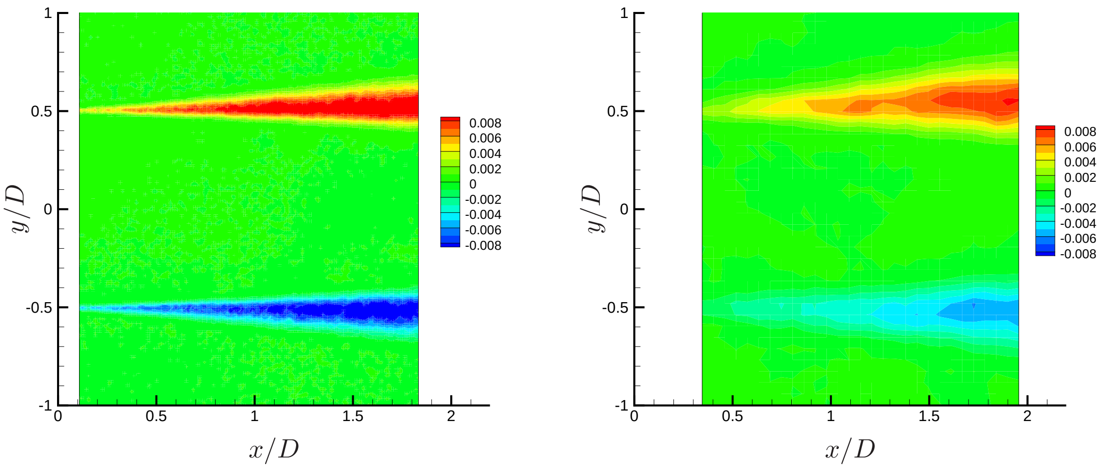


Figure 11: Mean velocity field normalized by centerline velocity $\left(\frac{U}{U_{cl}}\right)$ of a Mach 0.98 jet.



(a) (b)

Figure 12: Comparison of PIV data by $\frac{u'v'}{U_{cl}^2}$ in a Mach 0.98 flow: (a) present; (b) Ukeiley[18] results.

VIII. Conclusion

An anechoic chamber with a 2.1 m × 2.3 m × 2.5 m working volume has been constructed and demonstrated for noise measurements in Mach 0.4 to Mach 0.98 2.54 cm diameter jets. The steps taken to establish the performance of the facility were summarized. The facility has been validated by establishing that in the geometric far-field the sound pressure level scales with the inverse of distance squared, and that the OASPL follows the expected U_j^8 scaling. We also validate the spectra at 90° and 30° against existing data and find very good agreement. Complex nozzle geometries can be manufactured using a rapid protyping process. The capability to perform PIV measurements has been established and good agreement with existing data are again obtained. The ease of testing in a small anechoic structure as well as the low cost involved for model design and manufacture can provide an attractive alternative to testing in the larger facilities.

IX. Appendix

The relaxation frequencies for Oxygen and Nitrogen in Equation 2 are:[13–15]

$$f_{rO} = \frac{p_a}{p_r}\left(24 + 4.04 \times 10^4 h \frac{0.02 + h}{0.391 + h}\right) \tag{3}$$

$$f_{rN} = \frac{p_a}{p_r}\left(\frac{T}{T_r}\right)^{\frac{1}{2}}\left[9 + 280h \times \exp\left(-4.170\left[\left(\frac{T}{T_r}\right)^{-\frac{1}{3}} - 1\right]\right)\right] \tag{4}$$

$$h = h_{rel}\left(\frac{p_{sat}}{p_r}\right)\left(\frac{p_a}{p_r}\right)^{-1} \tag{5}$$

$$\log_{10}\frac{p_{sat}}{p_r} = -6.8346\left(\frac{T_o}{T}\right)^{1.261} + 4.6151 \tag{6}$$

h - Absolute Humidity (%)
h_{rel} - Relative Humidity (%)
p_{sat} - Saturated Vapor Pressure
T_o - Triple-Point Isotherm Temperature for Water (273.16K)

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